LCA Case Studies

# A Comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax

## Part 2: Comparative Assessment

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**Preamble.** Insulation of buildings is an important technology for saving heating energy and for a sustainable development. The results of a comparative LCA study of three insulation products applied for roof insulation are summarised in two parts. The products selected are based on HT stone wool representing traditional products - flax representing crop grown products and paper wool representing recycled products, respectively. Although the three materials have vastly different life cycles, they yet fulfil the same function; the methodology used should be of general interest.

**Part 1** of the paper [Int J LCA 9 (1) 53 – 66 (2004)] contains the project background, the goal and scope definition and three life cycle assessments for the three individual products, with a detailed inventory analysis, impact assessment, sensitivity analysis and interpretation. The actual comparison of the results from the three individual life cycle assessments is presented in **Part 2.** An attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials.

In general, paper wool has the lowest global and regional environmental impacts, and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption followed by cellulose and flax. The study also addresses occupational health issues using an approach similar to that for risk assessment. Here, the less biopersistent HT stone wool products are seen to be the safest alternatives, because of a low potential for exposure, sufficient animal testing, and the obvious absence of carcinogenic properties.

It must be recognised that insulation of buildings saves more than 100 times the environmental impacts associated with the production and disposal of the products used for insulation. Compared to that and the inherent uncertainties in the LCA, the differences between the investigated products are of minor environmental significance. Therefore, the main conclusion demonstrated in the study is that the quality and fitness of an insulation product is the most important aspect in the life cycle of insulation materials.

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**Abstract**

Part 2 summarises the results of a comparative LCA study of HT stone wool, flax representing crop grown products and paper wool representing recycled products applied for roof insulation, in which an attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials. Of the three products compared, paper wool has, in general, the lowest global and regional environmental impacts and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption, followed by cellulose and flax. The study also addresses occupational health, using an approach similar to that used for risk assessment. Here, the modern less biopersistent stone wool products are seen as the safest alternatives, because of a low potential for exposure, sufficient animal testing and the absence of carcinogenic properties. Overall, the differences between the investigated products are of minor environmental significance compared to that achieved by their use, namely insulation of buildings, which saves energy corresponding to more than 100 times the environmental impacts incurred in their manufacture. The main conclusion is that the quality and fitness for use of an insulation product throughout its useful life span is the most important aspect in the life cycle of insulation materials.

**Keywords**: Building insulation; case study; comparative LCA; flax; paper wool; stone wool

### 1 Introduction

The comparison between the three insulation systems is based on both the inventory results and the impact assessment. The main focus is on the impact assessment results, but the inventories provide more detail, especially with respect to the consumption of energy and fuels. Information from intermediate calculations, not shown in the paper, are used in some cases to provide even more detail with respect to the basic cause of the impacts and to give information of the sensitivity of the choices made throughout the study.

### 2 Comparison of Inventory Results

It is emphasized that the comparisons made between systems are based on inventories that have been established in very different ways. The stone wool inventory is mainly based on information from one production site, using a technology that is assumed to be representative for most other production sites. The inventory for flax insulation is a combination of average considerations and information from one producer, the representativity of which could not be established. The inventory for paper wool is based on a typical production process for newsprint in one country, combined with a representative recipe for the final product. Thus, the comparison considers three representative products, but especially for flax and paper wool insulation there may be appreciable differences to products made in other countries or with different technologies.

The inventory results of the three different insulation products used to fulfil the same functional unit are summarised in Table 1.

### 3 Comparison of Impact Assessment Results

The life cycle impacts of the three different insulation products used to fulfil the same functional unit are summarised in Table 2.

**Table 1:** Life cycle inventory results per functional unit for the three insulation systems

| Inventory results per functional unit | | Unit | Stone wool | Flax | Paper wool |
|---|---|---|---|---|---|
| **Energy** | Feedstock, fossil | MJ | 2.47 | 7.53 | 0.43 |
| | Fossil fuels | MJ | 14.14 | 20.31 | 6.32 |
| | Primary, fossil (total) | MJ | 16.61 | 27.84 | 6.75 |
| | Feedstock, renewable | MJ | 0.89 | 15.31 | 13.99 |
| | Renewable fuels | MJ | 0.18 | 0.00 | 1.36 |
| | Primary, renewable (total) | MJ | 1.07 | 15.31 | 15.35 |
| | Electricity | MJ | 3.07 | 6.58 | 4.14 |
| **Total energy consumption** | | MJ | **20.75** | **49.73** | **26.24** |
| **Resource depletion** | Water | g | 3907 | 5771 | 822 |
| | Biomass (incl. wood) | g | 42 | 945 | 1259 |
| | Minerals | g | 920 | 210 | 205 |
| | Waste minerals | g | 267 | 0 | 0 |
| | Scarce minerals (U as pure Uranium) | g | 0 | 0 | 0 |
| | Natural gas | g | 131 | 341 | 61 |
| | Oil | g | 77 | 293 | 106 |
| | Coal | g | 564 | 471 | 101 |
| | Ammonia | g | 5 | 0 | 0 |
| **Emissions to air** | $CO_2$ (fossil) | g | 1421 | 2142 | 805 |
| | CO | g | 105 | 2 | 1 |
| | SOx | g | 6.08 | 11.57 | 2.88 |
| | NOx | g | 2.47 | 7.44 | 3.74 |
| | $N_2O$ | g | 0.02 | 0.41 | 0.01 |
| | Methane | g | 1.04 | 4.19 | 0.57 |
| | HCl | g | 0.06 | 0.04 | 0.00 |
| | HF | g | 0.01 | 0.00 | 0.00 |
| | $H_2S$ | g | 0.03 | 0.00 | 0.00 |
| | Ammonia | g | 2.37 | 0.02 | 0.00 |
| | Hydrocarbons (except $CH_4$) | g | 0.21 | 2.20 | 1.22 |
| | VOC | g | 0.70 | 0.85 | 0.39 |
| | Particulates | g | 1.19 | 1.54 | 5.08 |
| **Emissions to waste water** | Suspended solids | g | 0.02 | 0.09 | 0.82 |
| | BOD | g | 0.00 | 0.19 | 0.84 |
| | COD | g | 0.05 | 0.37 | 6.66 |
| | Nitrogenous matter (as N) | g | 0.01 | 0.56 | 0.09 |
| | Phosphates (as P) | g | 0.00 | 0.00 | 0.00 |
| **Waste (solid)** | Hazardous | g | 0.5 | 0.4 | 1.7 |
| | Non-hazardous | g | 53 | 122 | 30 |
| | **Total waste** | g | **54** | **123** | **32** |

**Table 2:** Life cycle impacts for three different insulation materials used to fulfil the same functional unit

| Impact category | Unit | Stone wool | Flax | Paper wool |
|---|---|---|---|---|
| Global warming | g $CO_2$-equivalents | 1449 | 2357 | 819 |
| Acidification | g $SO_2$-equivalents | 12.3 | 17 | 5.5 |
| Nutrient enrichment CML-method | g $PO_4^{3-}$-equivalents | 1.16 | 1.22 | 0.7 |
| Nutrient enrichment EDIP-method | g $NO_3^-$-equivalents | 12.0 | 12.6 | 5.5 |
| Photochemical ozone creation | g $C_2H_4$-equivalents | 4.6 | 0.5 | 0.2 |
| Generation of solid waste | g non-hazardous waste | 53 | 122 | 30 |
| Generation of hazardous waste | g hazardous waste | 0.5 | 0.4 | 1.7 |
| Fossil fuels (incl. feedstock) | MJ | 16.6 | 27.8 | 6.8 |
| Renewable fuels (incl. feedstock) | MJ | 1.1 | 15.3 | 15.4 |
| Electricity | MJ | 3.1 | 6.6 | 4.1 |
| Total energy consumption | MJ | 20.6 | 49.7 | 26.2 |
| Water consumption | g water | 3907 | 5771 | 822 |

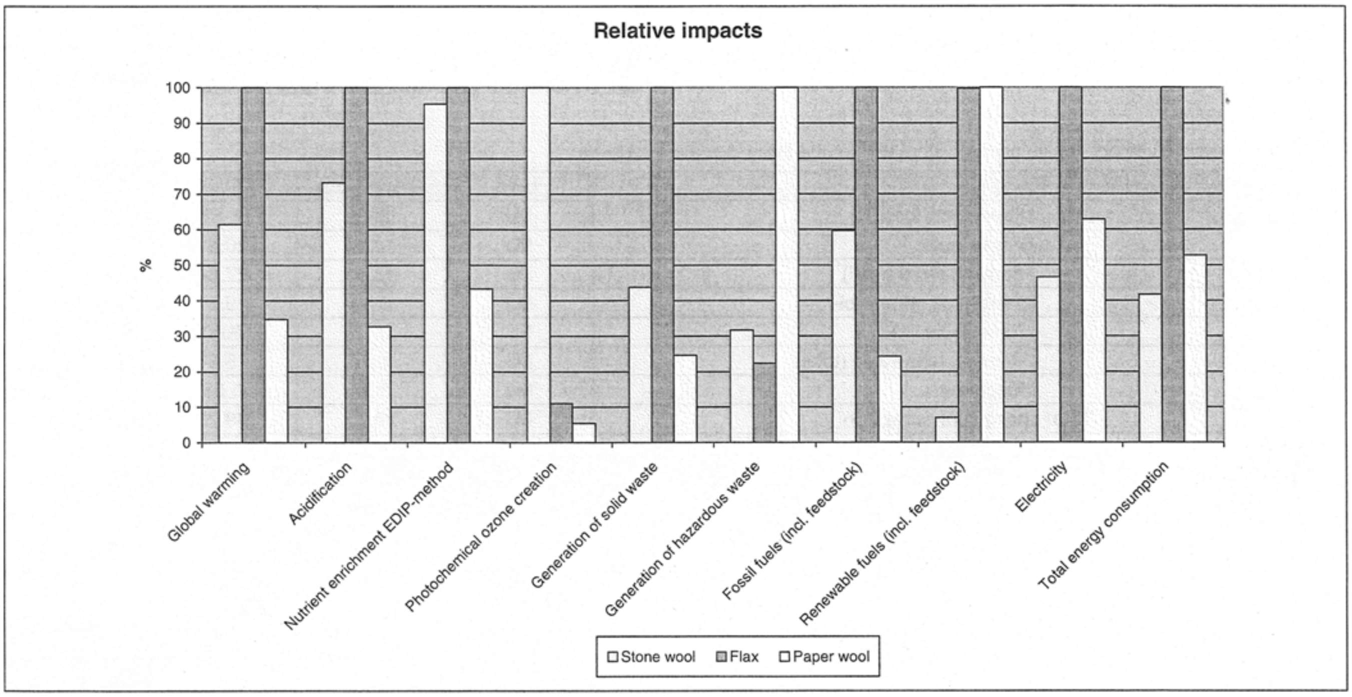


**Fig. 1:** Comparison of the contribution to different impact categories

As can be seen from the tables, the comparative picture is somewhat heterogeneous, and each of the impact parameters is therefore discussed in the following sections.

The contribution to different environmental impacts from the three very different insulation systems is illustrated in **Fig. 1**.

### 3.1 Global warming

The contribution to global warming differs by almost a factor 3 between the least contributing material (paper wool) and the most contributing (flax). It may be surprising that flax insulation, which in principle is based on a renewable resource, has the largest contribution. There are, however, a number of reasons for this. Growing of flax requires, like most other agricultural products, artificial fertilizers in order to give an economically sustainable yield. Production of fertilizers is relatively energy intensive, causing emissions of carbon dioxide. In the production, emissions of dinitrogen oxide ($N_2O$) occur and with $N_2O$ being a strong greenhouse gas, the contribution from fertilizer production becomes significant.

Furthermore, a fraction (1%) of the nitrogen compounds spread on the soil as fertilizer is assumed to transform and evaporate from the fields as $N_2O$, also contributing significantly in the overall result. The binder and flame retarding materials used to give the final products the desired technical properties use relatively large amounts of fossil fuels for their production. Emissions of carbon dioxide and methane from the combustion processes also contribute to the overall results.

Finally, the production process itself also contributes through emissions from its energy consumption. The energy is used to melt the binder materials before mixing with the flax raw material, but it is also assumed that some of the energy consumption is used for overhead, e.g. lighting and space heating.

The main contribution for stone wool insulation comes from the production process where fossil fuels are used for melting and production of energy. Production of stone raw materials is not very demanding in terms of energy consumption and there are no other emissions during their production that have a global warming potential. Binder materials are only used in small amounts and, besides emissions from energy consumption, there are no other known emissions that contribute to global warming in significant amounts.

Paper wool performs best with respect to global warming potential. Although the raw material for paper wool, old newsprint, primarily is based on renewable resources, its production still demands an input of fossil fuels and, accordingly, also causes emissions of carbon dioxide, which is the main contributor (more than 55%) in this system. Other significant sources are production of aluminium hydroxide and the final production, each contributing with 10–15%.

### 3.2 Acidification

The same picture is seen for acidification potential as for global warming potential, i.e. that flax insulation has the highest impact potential, and that it is about factor 3 higher than for paper wool and 40% higher than for stone wool. The main contribution in the flax system comes from production of binder and flame-retardants, constituting about 50% of the overall contribution. The production process contributes about 30%, while the impacts from flax growing contribute about 6%. The remaining contributions are distributed across a large number of processes and can be attributed to emissions of sulfur dioxide and nitrogen oxides from the combustion processes.

The main contribution in the stone wool system comes – not surprisingly – from the production process and is al-

most solely related to emissions of sulfur dioxide and nitrogen oxides from combustion of fossil fuels. It is not possible to distinguish between different production steps.

In the paper wool system, newsprint production contributes with about 35%, production of flame-retardants and biocides (especially aluminium hydroxide) with about 15%. Other significant contributions are the final production process (about 8%), and transportation by boat and truck of the newsprint from Finland to Central Europe (about 9%). The reason for the latter is that it is assumed that the boat transporting the newsprint is diesel powered with a fuel of a relatively high content (3%) of sulfur and having no emission control equipment. This may give an overestimation of the contribution to acidification, especially since it is uncertain whether emissions from boats at sea will reach areas where they may have an adverse effect.

### 3.3 Nutrient enrichment

There is some uncertainty associated with the assessment of the contribution to nutrient enrichment (eutrophication, nutrification), primarily because the inventory data are often of rather poor quality with respect to waterborne emissions of nitrogen and phosphorous containing compounds. The main conclusion, i.e. that the nutrient enrichment potential of the flax and stone wool systems are very similar while the contribution from the paper wool system is about half of that of the other two systems, should therefore be regarded cautiously.

The contribution from leaching of nitrogen in the flax system has not been included in the calculations due to lack of data. The importance of this is relatively small if system expansion is used, since similar emissions of nitrogen can be expected if the co-products (linseeds and grass hay) should be grown and harvested in separate systems. However, if economic allocation is used, the contribution to nutrient enrichment from the flax system increases by a factor 2 or more.

The main contribution in the paper wool and flax systems comes from airborne emissions of nitrogen oxides related to combustion of fossil fuels, contributing more than 80% of the total. In the stone wool system, the main contribution comes from emissions of ammonia in the final production process, accounting for about 75% of the total, while nitrogen oxides account for the major part of the remaining 25%. According to the EDIP method, emissions of COD do not contribute to nutrient enrichment, and play only a very minor role in either system when the CML impact assessment method is applied.

### 3.4 Photochemical ozone formation

The potential for photochemical ozone formation (POCP) differs from the previous impact categories with stone wool having a significantly larger contribution (factor 10–20) than the two other materials.

The main contributor to POCP in the stone wool system is carbon monoxide emitted from the production process. This accounts for about 80% of the total contribution. The emission is assumed to be associated with the use of coke as a fuel, however, this cannot be confirmed because the inventory is based on measurement of the emissions from the combined production process.

In the other two systems, the POCP is associated to a large number of small contributors, mainly industrial combustion processes. Whereas these account for only 20% in the stone wool system, they account for the total in the paper wool and flax systems, where only insignificant amounts of carbon monoxide are emitted.

However, even if the amount of carbon monoxide from stone wool production is reduced by installation of an afterburner similar to that used at the U.K. Rockwool® plant, stone wool will still have a larger contribution (factor 2–3) than the two other systems. This indicates strongly that there is a significant difference with respect to POCP between stone wool and the two other systems, but it should be noticed that the inventories for industrial combustion and production processes often are of a relatively low quality in relation to compounds contributing to POCP.

### 3.5 Hazardous waste

The handling of waste as a single or two impact categories causes some problems, because of the many waste definitions encountered when using inventory information from a broad range of sources. When combined, the inventories for the three products comprise no less than 18 waste categories, ranging from highly radioactive waste to waste for recycling (overburden waste has been omitted from the waste considerations).

It was chosen to aggregate five waste categories (hazardous, chemical, regulated chemicals, radioactive and highly radioactive) under the heading 'hazardous waste', while the remaining categories are aggregated under the heading 'non-hazardous waste'. This means that the sum results can only give a very crude indication of the performance of each system and that the comparison between the systems should be interpreted with great caution.

Also for hazardous waste, it is questionable whether the calculations give a realistic picture. As mentioned earlier, no international agreement has been achieved on the classification of different waste types in LCA, and the accumulated amounts can therefore hardly be compared on a more objective basis.

Thus, it is an open question whether the significant difference between the paper wool system and the other two systems is an expression of real-life conditions. The main contribution in the paper wool system comes from the newsprint production, with production of borax and boric acid being two other main contributions. Both sources for these inventories (KCL, Finland, and Borax Rio Tinto, USA) are assumed to be of relatively high quality, and it is therefore possible that the amounts give a realistic picture of classified waste fractions in the production. For stone wool, the main contribution comes from briquette production (more precisely to the energy consumption in cement production) and from the final production process. For flax, the contribution comes from numerous small sources. Overall, the results suggest that paper wool generates substantially more hazardous waste than either stone wool or flax. However, it is noted that the data quality – as for non-hazardous waste – is generally low.

### 3.6 Non-hazardous waste

The flax system produces the largest amount of non-hazardous waste of the three systems, 2.5–4 times more than

the other two systems. The main contribution comes from production of the electricity consumed in the production of insulation mats. The database used specifies that 14.1 g/MJ of 'bulky waste' results from electricity production, but it is not possible to get more specific information about the nature of the waste. A large fraction is assumed to be overburden from coal extraction, but this assumption cannot be verified from the information in the database. Another large fraction of the non-hazardous waste from electricity production is slags and ashes (3.25 g/MJ).

Other main contributions to the formation of solid waste in the flax system are mineral waste from production of PET and industrial waste from production of DAP. It has not been possible to establish more precise information for either of these amounts.

For stone wool, the main contribution comes from the final production process and is also associated with consumption of electricity. Other main contributions come from briquette production and from landfilling of PE-packaging waste; the latter constitutes about 20%.

For paper wool insulation, the main contribution comes from production of aluminium hydroxide and from the paper production process. Neither of these contributions is related to energy consumption, or at least only to a limited degree.

It is not possible to draw firm conclusions regarding waste amounts because of the rather poor quality and differences in waste categories of the basic data. The problem can only be solved satisfactorily by avoiding waste as an impact category, e.g. by a closer examination of the fate following disposal. Therefore, the figures given in the report are only crude suggestions of relative importance and should not be over-interpreted.

### 3.7 Energy consumption

The energy consumption has been assessed by looking at total primary energy consumption as well as for each of the subcategories for which information has been collected. There are, however, significant differences with respect to the types of energy used in the three systems, and these are discussed in more detail in the following sections.

### 3.8 Consumption of fossil fuels

When comparing the use of fossil fuels it is evident that the flax system is the most demanding, followed by the stone wool system (using 60% of the amount in the flax system) and paper wool (using only about 25% of the amount of the flax system).

The main reason for the comparatively large use in the flax system is the use of polyester binder, accounting for 15% of the weight of the final product. Polyester (PET) is – when compared to the other major raw materials examined in the present study – relatively demanding in terms of energy consumption in production (about 84 MJ/kg) and accounts for almost half of the fossil fuels used in the flax system. A large fraction (about 40%) is feedstock energy, which in principle can be recovered by incineration at the end of the useful life of the insulation. However, incineration is not seen as a common disposal process in the future, because the insulation material will be mixed with other demolition waste that only is suitable for recycling in road construction or other applications with low demands to material quality. The different disposal options are discussed in more detail in the sensitivity analysis of the flax system, but it is mentioned here that, in order to reach a comparable level of fossil energy consumption, at least 50% of the flax insulation must be collected separately from other construction materials and incinerated with recovery of the inherent energy. Another main consumption of fossil fuels takes place in the final production of flax insulation. Again, it can be assumed that the polyester binder is responsible to a large extent, because the binder needs energy to be melted and extruded as fibers.

The stone wool system examined in the current project performs very much in the same way with respect to fossil energy consumption as was reported by Bowdidge [1]. The production process is responsible for more than 90% of the fossil energy consumed, but the consumption in the present study is 10% less than reported by Bowdidge (16.6 MJ/kg vs. 18.4 MJ/kg). This difference can probably be attributed to differences in process efficiency and/or a better energy management at the Danish production site.

In the paper wool system, newsprint production accounts for about 50% of the consumption of fossil fuels, production of additives accounts for 40%, and transportation for about 10%. As for the flax system, disposal by energy recovery is not assumed to be a common disposal method in the future. The possibilities are perhaps even less for paper wool because of the state of the material following demolition. However, it is mentioned here that incineration of 50% of paper wool following the use phase will decrease the consumption of fossil fuels to only about 2 MJ/kg, because the renewable fuel paper wool will displace fossil fuels in production of heat and electricity.

### 3.9 Consumption of renewable fuels

The paper wool and flax systems consume equal amounts of renewable fuels, about 20 times more than the stone wool system. For paper wool, the main part (more than 95%) of the renewable fuel is feedstock (wood) in the basic raw material, newsprint. As discussed in the previous section, it is theoretically possible to recover a large part of the inherent energy by incineration, but the nature of the paper wool waste makes this option less viable, also in the future. If incinerated, the flame-retardants (borax, boric acid and aluminium hydroxide) will decrease the heat value of the paper. This decrease is included in the calculations that are based on actual measurements of the heating value of final products that can be found on the market today. The consumption of renewable fuels in the flax system is also primarily related to the feedstock content in the product.

### 3.10 Electricity consumption

The flax system consumes most electricity of the three systems, more than twice the amount of the stone wool system and about 50% more than the paper wool system. For flax and stone wool, the main part of the electricity consumption takes place in the final production stage, while for paper wool the main consumption is found in the production of newsprint.

### 3.11 Overall energy consumption

The flax insulation system has the largest total primary energy consumption, 250% larger than the stone wool system and twice as large as the paper wool system. Stone wool insulation is the least demanding with respect to overall consumption of primary energy, consuming only 40% of that for flax and 80% of that for paper wool. The largest part of the energy consumed in the stone wool system is based on fossil fuels, but even when taking this aspect into consideration, stone wool performs significantly better than flax insulation. Paper wool is the least demanding with respect to fossil fuels (about 40% of the consumption in the stone wool system), but with respect to the overall consumption, paper wool consumes more energy, primarily because of the large amounts of feedstock in the product that cannot be exploited following use.

## 4 Comparison of Health Aspects

Adverse effects of concern for fibres are mechanical skin irritation caused by friction of coarse fibres and a possible hazard of developing respiratory diseases including fibrosis and cancer.

### 4.1 Stone wool

Due to the effect of coarse fibres, Commission Directive 97/69/EEC classifies mineral wool (including stone wool) as a skin irritant with risk phrase R38.

In a review article from 1996 it is concluded that there is no convincing evidence that exposure to mineral wool (stone and glass wool) is a risk factor for impaired lung function or fibrosis in the lung [2].

In recent years, HT stone wool (high-alumina, low-silica wools) has been increasingly replacing traditional wool [3]. The reasoning behind being that the potential danger of a specific fibre is mainly dependent upon the extent to which the fibres can be inhaled and can persist in the lung [4]. The lower the biopersistence (or the higher the biosolubility) the less potential pathogenic is a specific fibre type. The development and implementation of the less biopersistent HT stone wool, instead of traditional stone wool, has increased the safety margins in manufacturing and use of fibrous insulation materials [3,5,6].

Mineral wool (stone wool, glass wool) is within the EU by Commission Directive 97/69/EEC classified as carcinogenic in Category 3 (possibly carcinogenic). However, 'Note Q'[1] in the EU Commission Directive 2001/59/EC of 6 August 2001 allows for derogation (exemption) from classification as a carcinogen. The animal test results according to 'Note Q' for the HT stone wool fibres were below regulatory thresholds and were therefore not classified as carcinogens within the EU [6].

Also, the HT fibres have previously been tested in a long-term inhalation study in rats and produced no lung fibrosis and no significant increase in the incidence of lung tumours and no mesothelioma [5]. In addition, in a study in rats HT fibres administered by intraperitoneal injection (i.p.) at a high dose showed no abdominal tumours [7].

A recently published investigation evaluated to what extent various insulation materials (including stone wool, flax and paper wool) influenced the working environment. To ensure a high degree of comparability between the different materials, the tests were done at full-scale simulation in an experimental hall. It was concluded that the installation of HT stone wool could be performed without use of respiratory protection [8].

### 4.2 Paper wool

In comparison, paper dust has been shown to cause cancer by injection in test animals as well as lung fibrosis by inhalation [9,10]. Furthermore, paper fibre is biopersistent [11] and the dust formation during handling often exceeds the Threshold Limit Values, requiring the use of respiratory protection in the work situation [8]. The potential for paper dust to cause cancer by inhalation has not been investigated, and this is a knowledge gap, which should be rectified.

### 4.3 Flax wool

The toxicological properties of flax fibres are, to a large extent, unknown. Exposure to flax dust is a well-known cause of the lung disease byssinosis (Greek: *byssinosis* = flax) [12], but the carcinogenic properties and the potential for causing lung fibrosis have not been investigated in any detail. By analogy to paper fibre, flax is assumed to be biopersistent and the potential for dust formation warrants the use of respiratory protection [8].

### 4.4 Additives

Organic based insulation materials are flammable and need addition of flame-retardants and sometimes biocides. The most common flame-retardants are boron compounds or aluminium compounds. Ingestions of boric acid or borax in drinking water or food have caused testicular damage in experimental animals, and boron compounds have been classified by the EU Working Group on Classification and Labelling of Dangerous Substances as reproductive harmful with R-phrase 62 (possible risk of impaired fertility) and R-phrase 63 (possible risk of harm to the unborn child). The aluminium compounds used as flame retardant in these insulation products are not considered hazardous by the EU. The results of the human health assessment are summarised in **Table 3**.

## 5 Ranking of the Three Product Systems

In **Table 4**, the three product systems have been ranked according to their performance in each impact category. This subjective assessment is based on actual differences between the systems in combination with the overall data quality of the LCA's performed and the precision of the impact assessment methods for each impact category.

[1] Note Q: The classification as a carcinogen need not apply if it can be shown that the substance fulfils one of the following conditions:
- a short term biopersistence test by inhalation has shown that fibres longer than 20 μm have a weighted half-life less than 10 days, or
- a short term biopersistence test by intratracheal instillation has shown that fibres longer than 20 μm have a weighted half-life less than 40 days, or
- an appropriate intra-peritoneal test has shown no evidence of excess carcinogenicity, or
- absence of relevant pathogenicity or neoplastic changes in a suitable long term inhalation test.

**Table 3.** Comparison of animal and human evidence for chronic effects and possible exposure levels relative to Occupational Exposure Limits (OELs)

| Fiber dust | Animal evidence | | | | Human evidence | | Exposure |
|---|---|---|---|---|---|---|---|
| | Carcinogenicity | | Lung fibrosis by inhalation | Biopersistence | Non-malignant lung disease | Cancer (IARC) | OEL[2] Exceeded (Breum et al. 2002) |
| | Inhalation | Injection | | | | | |
| Traditional stone wool | No | Yes | Yes | No | No | No | No |
| HT stone wool | No | No | No | No | No[3] | No[3] | No |
| Cellulose shredded paper | Not tested | Yes | Yes | Yes | Not tested | Not tested | Yes |
| Cellulose flax | Not tested | Not tested | Not tested | (Yes)[1] | Yes | Not tested | (Yes) |

1) No experiments have been performed but the fibers are most likely biopersistent (durable) in lung due to chemical/physical similarity to other cellulosic fibers.
2) OEL for unspecified organic dust = 3 mg/m$^3$ total dust; OEL for organic fibers do not exist but the OEL as for stone wool = 1 respirable fibers./cm$^3$ has been used.
3) Due to similarities to traditional stone wool in chemical components.

**Table 4:** Ranking of the three product systems with respect to different impacts (1 = best, 3 = worst, ? indicates that there is no available information, and * indicate that the differences are evaluated to be significant within the given system boundaries)

| Impact category | Unit | Stone wool | Flax | Paper wool |
|---|---|---|---|---|
| Global warming | g $CO_2$-equivalents | 2* | 3* | 1* |
| Acidification | g $SO_2$-equivalents | 2 | 3 | 1* |
| Nutrient enrichment CML-method | g $PO_4^{3-}$-equivalents | 2 | 3 | 1* |
| Nutrient enrichment EDIP-method | g $NO_3^-$-equivalents | 2 | 3 | 1* |
| Photochemical ozone creation | g $C_2H_4$-equivalents | 3 | 2 | 1 |
| Generation of solid waste | g non-hazardous waste | 2 | 3* | 1 |
| Generation of hazardous waste | g hazardous waste | 2 | 1 | 3* |
| Fossil fuels (incl. feedstock) | MJ | 2* | 3* | 1* |
| Renewable fuels (incl. feedstock) | MJ | 1* | 2 | 3 |
| Electricity | MJ | 1 | 3* | 2 |
| Total energy consumption | MJ | 1 | 3* | 2 |
| Water consumption | g water | 2 | 3 | 1 |
| Health aspects in general | | 1 | 3 | 2 |
| Carcinogenicity in animals | | 1* | Not tested | 3 |
| Lung fibrosis in animals | | 1* | Not tested | 3 |
| Fiber biopersistence in animals | | 1* | 3 | 3 |
| Non-malignant lung disease in humans | | 1 | 3 | ? |
| Skin irritation in humans | | 3 | ? | ? |
| Reaction to fire | | 1* | 3 | 3 |

It is a general picture that flax insulation is most demanding in the examined impact categories, with formation of photochemical ozone and generation of hazardous waste being the exceptions. This may be somewhat surprising as flax in itself is a renewable material, but is explained by the use of a relatively large consumption of non-renewable materials as important components in the product. This consumption adds significantly to both energy consumption (incl. fossil fuels) and the examined impact categories that, to a large extent, are related to emissions from energy consumption.

Another general picture is that the paper wool system performs best in most impact categories, with total energy consumption and generation of hazardous waste being the exceptions. This cannot be regarded as a surprise, as paper wool, to a large extent, is based on renewable resources and only consumes a relatively small amount of non-renewable resources which themselves are relatively undemanding in terms of consumption of fossil fuels.

The performance of the stone wool system lies in between flax and paper wool in most of the examined impact categories, with total energy consumption being an important exception. The stone wool system consumes a relatively large amount of fossil fuels in the production phase, but none of the raw materials entering the system are demanding in terms of non-renewable resources. As evidenced by the contribution to photochemical ozone formation, it is still possible to improve the environmental performance in specific areas (and at specific production sites), but stone wool must generally be regarded as a fully developed product system providing a sustainable option.

With respect to health aspects, it is concluded that modern HT stone wool is neither carcinogenic nor does it cause serious lung diseases. It is more biosoluble than traditional stone wool and there is no (or minimal) risk of exceeding the occupational exposure limits. In comparison, paper dust has been shown to cause cancer by injection in test animals as well as lung fibrosis by inhalation. The potential for causing cancer by inhalation in animals has not been investigated. The toxicological properties of flax fibers are, to a large extent, unknown. Exposure to flax dust is a well-known cause of byssinosis but the carcinogenic properties and the potential for causing lung fibrosis have not been investigated

in any detail. The missing investigations on paper dust and flax fibers are of great concern, also because there is a great risk of exceeding occupational exposure limits during handling. Use of respiratory protection is therefore a must when handling the two materials. Based on available information the potential health hazard ranking for these three materials are: stone wool < paper wool < flax.

As a final remark, it is emphasized that each of the systems, irrespective of their environmental performance during production and disposal, has a positive influence on the environment because of their ability to reduce energy consumption in buildings. The energy savings during use amounts to more than 100 times of the invested energy, and the benefits from adding more insulation will clearly outweigh any drawbacks from the production and distribution, also when national requirements have already been fulfilled.

There are still major opportunities for improvement with respect to the final disposal of especially flax and paper wool, at least in relation to the basic recycling assumption that has been applied in the present study. For flax and paper wool incineration by energy recovery seems to the best alternative, unless producers can find a way of re-using the products after their first life in a building. Re-use should however only be applied if absolute certainty of insulating properties can be obtained, because otherwise a large and unnecessary heat loss may be the consequence. For stone wool, it is possible to re-use waste products, and this will cause a smaller consumption of (abundant) stone materials.

## 6 Final Conclusions and Outlook

It is acknowledged that the study is scoped to cover only a part of the insulation products on the market today, because it is a comparison between products based on two organic materials with one traditional mineral material. A comparison with glass wool, polystyrene and polyurethane products would also be interesting. The study pinpoints some main characteristics of three important materials, not only in relation to their impacts on the natural environment, but also to occupational health, which for many construction companies and workers are seen as an equally important issue.

With respect to potential environmental impacts, stone wool and paper wool are the most preferred materials. Stone wool has the smallest consumption of primary energy over the whole life cycle, whereas paper wool performs best with respect to environmental impact categories like global warming, acidification, photochemical ozone creation and nutrient enrichment. Flax insulation has the largest impacts of the three materials in most of the impact categories examined in the study, caused, to a large extent, by the binder used, which is an essential component.

The differences in environmental impacts from the production and disposal of the three materials are, in this context, only of minor importance. The quality of the products (their fitness for use throughout their entire life time) may in the end prove to be the determining factor, because a reduction in the insulation capacity will cause much larger impacts than those observed during the production and disposal of the products.

With respect to occupational health and safety, stone wool emerges as a material with a thorough documentation for its toxicological properties. The toxicological properties of flax and paper wool are not documented to the same extent. Absence of serious potential impacts on human health is seen as an integral part of product quality, and for that adequate documentation is missing for paper wool and flax. Based on available data, HT stone wool seems to be the most tested, well-known and safest choice of the three as regards potential health hazards.

Finally, it must be recognised that in the long run insulation of buildings by saving energy probably saves more than 100 times the environmental impacts associated with the production and disposal of the products used for insulation. Thus, all three insulation products examined with respect to their potential impacts on the environment and human health provide a large benefit to the environment in the life cycle perspective. The quality and fitness for use of an insulation product throughout its useful life may be the most important aspect. Seen in view of this and the inherent uncertainties in the LCA, the differences between suitable products are of minor significance as demonstrated in the present study.

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